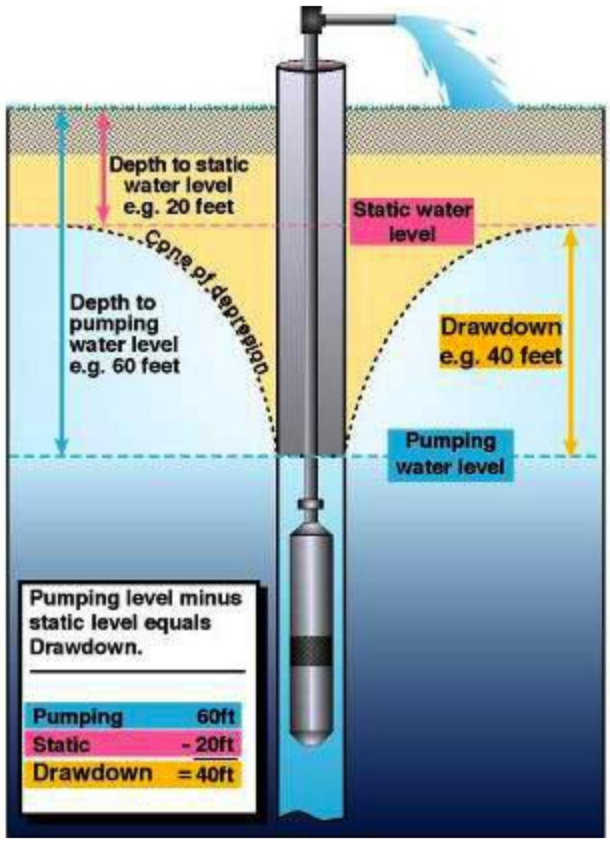
State of Ohio
Environmental Protection Agency

Division of Drinking and Ground Waters

Technical Guidance Manual for Ground Water Investigations

Chapter 4

Pumping and Slug Tests



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TECHNICAL GUIDANCE
MANUAL FOR
GROUND WATER INVESTIGATIONS

CHAPTER 4

Pumping and Slug Tests

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PREFACE

This chapter contains guidance for conducting and reporting on pumping and slug tests at sites that are being characterized because of suspected or known contamination, or are being evaluated for waste disposal. This chapter does not cover pumping tests for determining whether a ground water zone is capable of producing a sufficient yield for supply purposes.

This document is part of a series of chapters incorporated in Ohio EPA's *Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring* (TGM), which was originally published in 1995. DDAGW now maintains this technical guidance as a series of chapters rather than as an individual manual. The chapters can be obtained at http://www.epa.state.oh.us/ddagw/tgmweb.aspx.

The TGM identifies technical considerations for performing hydrogeologic investigations and ground water monitoring at potential or known ground water pollution sources. The purpose is to enhance consistency within the Agency and inform the regulated community of the Agency's technical recommendations and the basis for them. In Ohio, the authority over pollution sources is shared among various Ohio EPA divisions, including the Emergency and Remedial Response (DERR), Hazardous Waste Management (DHWM), Solid and Infectious Waste (DSIWM), and Surface Water (DSW), as well as other state and local agencies. DDAGW provides technical support to these divisions.

Ohio EPA utilizes ***guidance*** to aid regulators and the regulated community in meeting laws, rules, regulations and policy. Guidance outlines recommended practices and explains their rationale. The Agency may not require an entity to follow methods recommended by this or any other guidance document. It may, however, require an entity to demonstrate that an alternate method produces data and information that meet the pertinent requirements. The procedures used to meet requirements usually should be tailored to the specific needs and circumstances of the individual site, project, and applicable regulatory program, and should not comprise a rigid step-by-step approach that is utilized in all situations.

Major Changes from the February 1995 TGM

The Ohio EPA Technical Guidance Manual for Hydrogeologic Investigations and Ground Water Monitoring (TGM) was finalized in 1995. This guidance document represents an update to Chapter 4 (Pumping and Slug Tests). Listed below are the major changes from the 1995 version.

1. Simplified the tables summarizing the various test analysis methods by removing detailed information that a reader could only understand if they were familiar with the details of the method.

2. Removed figures. Problems were encountered with obtaining permission to use figures from sources other than government documents.

3. Updated references.

4. Placed less focus on workplans and more on what and how pump and slug test data should be submitted.

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CHAPTER 4

PUMPING AND SLUG TESTS

Slug and pumping tests are used to determine in-situ properties of water-bearing formations and define the overall hydrogeologic regime. Such tests can determine transmissivity (T), hydraulic conductivity (K), storativity (S), yield, connection between saturated zones, identification of boundary conditions, and the cone of influence of a pumping well in a extraction system. The hydraulic properties that can be determined are particular to the specific test method, instrumentation, knowledge of the ground water system, and conformance of site hydraulic conditions to the assumptions of the test method (ASTM 4043-96(2004). The selection of test method(s) depends primarily on the hydrogeology of the area being tested. Secondarily, the method is selected based on the testing conditions specified by a particular method, such as the method of stressing or causing water level changes in the ground water zone being evaluated and the requirements to observe water level responses.

To ensure proper test design, it is important to define objectives and understand site hydrogeology as much as possible. Methods, instruments, and operating procedures should be specified in a workplan. The results of tests, methods, and any departures from the workplan that were necessary during implementation should be documented in a report.

The purpose of this document is to aid in the design and performance of slug and pumping tests, provide recommended quality assurance and quality control (QA/QC) procedures, and present a standardized approach to the presentation of the resulting data. This chapter covers various types of tests, including single well and multiple well. Their advantages and disadvantages and the minimum criteria that should be considered prior to, during, and after implementation are summarized. The recommendations presented here are a subset of the larger hydrogeologic characterization process that is implemented when characterizing a site. The additional investigative tools necessary to adequately characterize a site, as well as recommendations for their use, are contained in other chapters of the Technical Guidance for Manual for Hydrogeologic Investigations and Ground Water Monitoring (TGM). This chapter does not cover pumping tests conducted for the purpose of determining whether a ground water zone is capable of producing a sufficient amount of yield for water supply purposes.

SLUG TESTS

Slug tests are generally conducted to determine the horizontal K of a ground water zone. A slug test involves the abrupt removal, addition, or displacement of a known volume of water and the subsequent monitoring of changes in water level as equilibrium conditions return. The measurements are recorded and analyzed by one or more methods. The rate of water level change is a function of the K of the formation and the geometry of the well or screened interval.

Slug tests generally are conducted in formations that exhibit low K. They may not be appropriate in fractured rock or formations with T greater than 250 m^2/day (2,690 ft^2/day) (Kruseman and de Ridder, 1990). However, in some instances, a vacuum or slug test conducted with a pressure transducer or an electronic data logger may be warranted.

Hydraulic properties determined by slug tests are representative only of the material in the immediate vicinity of the well. However, by performing a series of slug test at discrete vertical intervals and tests in closely spaced wells, important information can be obtained about the vertical and horizontal variations of hydraulic properties for the site (Butler, 1998). It should be noted that due to the localized nature of hydraulic response, the test might be affected by the properties of the well filter pack. Therefore, the results should be compared to known values for similar geologic media to determine if they are reasonable.

If slug tests are used, the designer should consider the amount of displaced water, design of the well, number of tests, method and frequency of water level measurements, and the method used to analyze the data. Slug tests should be conducted in properly designed and developed wells or piezometers. If development is inadequate, the smearing of fine-grained material along the borehole wall may result in data that indicate an artificially low K. This may lead to an underestimation of contaminant migration potential. Drilling methods, well design and installation, and well development are covered in Chapters 6, 7 and 8, respectively. The design, analytical methods, and information that should be reported to document that the tests were conducted properly are discussed briefly below. Detailed practical guidelines for the design, performance, and analysis of slug tests are provided by Butler (1998). Additional information can also be found in Black (1978), Chirlin (1990), Dawson and Istok (1991), Ferris et al. (1962), Kruseman and de Ridder (1990), and Lohman (1972), Batu (1988), and ASTM standards.

For some programs, workplans may need to be submitted prior to conducting tests to ensure that results will be relevant to regulatory and program goals. If needed, the workplan should discuss the components listed below for the design and performance of the slug tests and the method of analysis.

DESIGN AND PERFORMANCE OF SLUG TEST

Design of Well

Well depth, length of screen, screen slot size and length, and distribution of the filter pack should be known and based on site-specific boring information for a well to be used as a valid observation point. For example, equations used in data analysis incorporate the radii of the well and borehole. The nature of the materials comprising the screened interval (i.e., thickness, grain size, and porosity of the filter pack) also must be known. Monitoring well construction recommendations are provided in TGM Chapter 7.

Number of Tests

Properties determined from slug tests at a single location are not very useful for site characterization unless they are compared with data from tests in other wells installed in the same zone. When conducted in large number, slug tests are valuable for determining subsurface heterogeneity and isotropy. The appropriate number depends on site hydrogeologic complexity.

Test Performance and Data Collection

Data collection should include establishment of water level trends prior to and following the application of the slug. Pre-test measurements should be made until any changes have stabilized and should be taken for a period of time, at least as long as the expected recovery period. Water level measurements in low-permeability zones may be taken with manual devices. Automatic data loggers should be used for tests of high permeability zones. Slug tests should be continued until at least 85-90 percent of the initial pretest measurement is obtained (U.S. EPA, 1986).

Whenever possible, water should be removed by either bailing or it should be displaced by submerging a solid body. According to Black (1978), an addition of water invariably arrives as an initial direct pulse followed by a subsequent charge that runs down the sides of a well. This may result in a response that is not instantaneous, which may subsequently influence the data (Figure 4.1). An advantage of displacement is that it allows for collection and analysis of both slug injection and slug withdrawal data. However, slug injection tests should not be conducted in wells where the screened interval intercepts the water table.

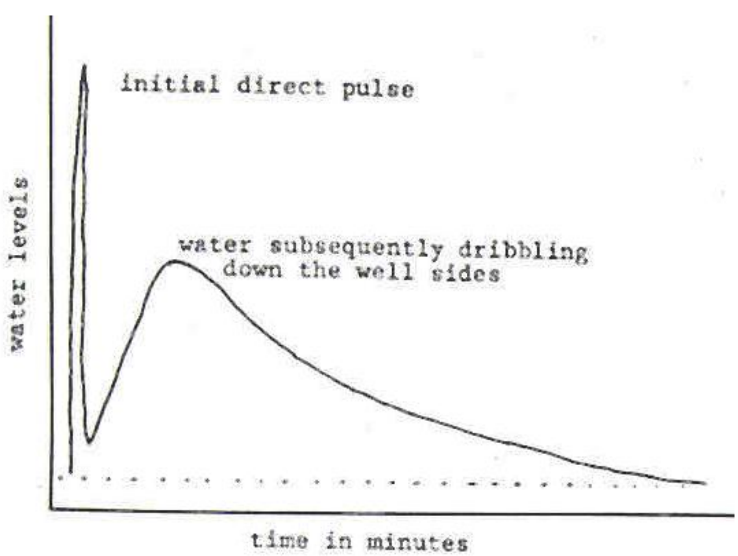

Figure 4.1 Results of a slug test with addition of water. Water arrives as an initial direct pulse followed by a subsequent charge that runs down the sides of the well (Source: Adapted from Black, 1978)**.**

The volume of water removed or displaced should be large enough to insure that build-up or drawdown can be measured adequately, but it should not result in significant changes in saturated zone thickness (Dawson and Istok, 1991). It should be large enough to change water level by 10 to 50 centimeters (Kruseman and de Ridder, 1990). Field procedures for slug tests are also described in ASTM D 4044-96(2002).

Modified Slug Tests

In addition to removal or displacement of water, a change in static water level can be accomplished by pressurizing a well with air or water or by creating a vacuum. Packers are often used to seal the zone to be tested.

Packer Tests within a Stable Borehole

Horizontal K for consolidated rock can be determined by a packer test conducted in a stable borehole (Sevee, 2006). A single packer system can be used when testing between a packer and the bottom of the borehole. Two packer systems can be utilized in a completed borehole at any position or interval. A packer is inflated using water or gas. Water should be injected for a given length of time to test the packed-off zone.

Pressure Tests

A pulse or a pressure test may be appropriate in formations where K can be assumed to be lower than 10^{-7} cm/sec. In a pulse test, an increment of pressure is applied into a packed zone. The decay of pressure is monitored over a period of time using pressure transducers with electronic data loggers or strip-chart recorders. The rate of decay is related to the K and S of the formation being tested. This test generally is applied in rock formations characterized by low K. Compensation must be made for skin effects[1] and packer adjustments during the test. An understanding of the presence and orientation of fractures is necessary to select an appropriate type curve to analyze test data (Sevee, 2006 and Sara, 2003). ASTM D4631-95 (2002) describes the pressure-pulse technique applied to low hydraulic conductivity bedrock.

Vacuum Tests

According to Orient et al. (1987), vacuum tests can be used to evaluate the K of glacial deposits and compare favorably to more conventional methods. In general, water level is raised by inducing vacuum conditions. Once it reaches the desired height and sufficient time has been allowed for the formation to return to its previous hydrostatic equilibrium, the vacuum is broken and the recovery is monitored. The data is evaluated using the same techniques that are used to evaluate conventional slug test data.

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[1]Skin effects result from locally increasing the K near the well by opening fractures (positive skin) or decreasing the K (negative skin) by filling voids or coating borehole walls with drilling cuttings (Sevee, 2006).

ANALYSIS OF SLUG TEST DATA

Mathematical methods/models for slug test data analysis are summarized in Table 4.1. Methods have been developed to deal with confined, unconfined, partial penetration, and skin effects. Calculation of K for a fully screened zone is achieved by dividing T by the entire thickness of the zone. A test of a partially penetrating well yields a T value that is only indicative of that portion of the zone that is penetrated by the well screen. Results should not be "over-interpreted". The values obtained are for the geologic material immediately surrounding the well intake, which invariably has been altered to some degree by the installation process.

Computer programs are available to evaluate slug test data. Only those programs that provide analysis of the data based on graphical curve matching, rather than simply least-squares analysis, and allow for the generation of data plots should be used.

Table 4.1 Analysis Methods for Slug Tests.

GENERAL ASSUMPTIONS

1. The ground water zone has an apparently infinite areal extent.
2. The zone is homogeneous and of uniform thickness over the area influenced by the test (except when noted in application column).
3. Prior to the test, the water table or piezometric surface is (nearly) horizontal over the area influenced and extends infinitely in the radial direction.
4. The head in the well is changed instantaneously at time $t_o = 0$.
5. The inertia of the water column in the well and the linear and non-linear well losses are negligible (i.e., well installation and development process are assumed to have not changed the hydraulic characteristics of the formation).
6. The well diameter is finite; hence storage in the well cannot be neglected.
7. Ground water density and viscosity are constant.
8. No phases other than water (such as gasoline) are assumed to be present in the well or ground water.
9. Ground water flow can be described by Darcy's Law.
10. Water is assumed to flow horizontally.

	APPLICATION				
METHOD	**Ground Water Zone Type**	**Flow Condition**	**Can account for**		**REMARKS**
			Partial Penetration	Anisotropic	
Cooper et al. (1967) (a,b,c)	Confined	Transient	No	No	Also described in ASTM D4104-91 (1992)
Bouwer and Rice (1976) Bouwer (1989) (a,b,c)	Unconfined or leaky*	Steady state	Yes	No	Can be used to estimate the K of leaky ground water zones that receive water from the upper-semi confining layer through recharge or compression
Hvorslev (1951) (a, c)	Confined or Unconfined	Transient	Yes	Yes	Differences of 0.3X to 0.5X can be observed when comparing the K calculated from other methods In some cases can be applied to unconfined ground water zones, Fetter (2001)
Bredehoeft and Papadopulos (1980)	Confined	Transient		Yes	Low to extremely low K (i.e. silts, clays, shales)
Uffink (1984) (Oscillation Test) (b)	Confined	Transient		No	

Described in : a-Dawson and Istok (1991). b- Kruseman and de Ridder (1990); c-Butler (1998)

PRESENTATION OF SLUG TEST DATA

The specifics of slug tests should be documented to demonstrate that the tests were conducted properly and that the data and interpretations are representative of site conditions. At a minimum, the following, should be specified:

- The design and implementation of the test including:

- Well construction (e.g., depth and length of screen and filter pack).

- Method to displace the water, such as:

    - Dimension and weight of slug.
    - Composition of slug.
    - Manner in which the slug will be lowered and raised from the well.
    - Use of packers, and manner in which pressure will be delivered
    - Chemical quality of water to be added.

- Frequency and method of water level measurements.

- Number and location of tests.

- All raw data.

    - Method. Programs used for analysis should be referenced and all assumptions and limitations should be noted. For methods that employ type curves curve matching, the following should be provided.

    - The portion of data to which type curves are fit should be indicated on the plot.

    - If an analysis method employing a family of type curves is used, all curves selected to fit the data should be described.

- All data plots. Plots of change in hydraulic head versus time should be presented for all slug-tested wells. Plots should be on an arithmetic scale, and either double-logarithmic or semi-logarithmic scale, depending on the analysis technique. Time data should be depicted along the horizontal axis, and change in head along the vertical axis. All data points should be clearly labeled and identified in a legend. If multiple tests are presented on the same plot, the labeling should be distinct to differentiate between data sets.

- Sample calculations. Equations used for calculating hydraulic properties should also be included. While calculations of the values (e.g. hydraulic conductivity, estimated transmissivity) can be presented on the data plots, the values themselves should be presented in tabular format in the report for all slug tested wells, all zones tested, and each data analysis method used:

- Any field conditions or problems that may influence the results.

- An evaluation and interpretation of the data (relating it to overall site conditions). In the event that calculations are available from other multiple-or single-well tests, the report should contain a discussion addressing how the most recent calculations compare with previously obtained values.

SINGLE WELL PUMPING TESTS

A single well test involves pumping at a constant or variable rate and measuring changes in water levels in the pumped well during pumping and recovery. Single well pumping tests can be used to determine transmissivity, hydraulic conductivity, and yield of a ground water zone. They are also conducted to determine well loss, and optimizing rate and pump setting for a multiple well test. Single well tests are often used when water level recovery is too rapid for slug tests and no observation wells or piezometers are available. Single well tests generally will not identify impermeable boundaries, recharge boundaries, or interconnection between other ground water or surface water unless these conditions exist in very close proximity to the well being tested.

A step drawdown test is a type of single well test that is often used to optimize appropriate pumping rate and depth of pump setting used in a multiple well test (Domenico and Schwartz, 1998). This test involves pumping at a constant rate for a period of time, the rate is then increased. This process generally is repeated through a minimum of three steps. The duration of each step generally should be a minimum of 60 minutes and should be long enough such that drawdown data plotted on a semilog plot fall on a straight line. References detailing the mechanics of a step test include Kruseman and de Ridder (1990), Driscoll (1986), Dawson and Istok (1991), and Batu (1998), and Walton (1996).

The drawdown in a pumped well is influenced by well loss and well-bore storage. Well loss is responsible for drawdown being greater than expected from theoretical calculations and can be classified as linear or non-linear. Linear loss is caused by compaction and/or plugging of subsurface material during well construction and installation and head loss in the filter pack and screen. Non-linear loss includes head loss from friction within the screen and suction pipe.

Since well-bore storage is large when compared to an equal volume of formation material, it must be considered when analyzing drawdown data from single well tests (Kruseman and de Ridder, 1990). The effects of well-bore storage on early-time drawdown data can be recognized by a log-log plot of drawdown (s_w) verses time (t). Borehole storage effects exist if the early-time drawdown data plots as a unit-slope straight line (Kruseman and de Ridder, 1990). Papadopulos and Cooper (1967) observed that the influence of well-bore storage on drawdown decreases with time (t) and becomes negligible at

$$t = 25 r_c^2 / KD$$

where:

r_c = is the radius of the unscreened part of the well
K = hydraulic conductivity
D = thickness of saturated zone.

ANALYSIS AND PRESENTATION OF SINGLE WELL PUMPING TESTS

Table 4.2 presents several methods for analyzing drawdown data for constant discharge, variable discharge, and step-discharge single well tests. Analysis of recovery test data (residual drawdown) is valuable with a single well pumping test. Methods for analysis are straight line methods, which are the same as for conventional pumping tests. However, with single well tests, one must account for the effects of well-bore storage when evaluating recovery (Kruseman and de Ridder, 1990). Recovery data may be more reliable then data collected during the pumping phase because pumping does not influence recovery. Available methods to analyze recovery are discussed in the Multiple Well Pumping Tests section of this chapter.

Information to document that single well tests have been appropriately performed and analyzed may be similar to documentation for either slug or multiple well pumping tests.

Table 4.2 Single well pumping tests.

GENERAL ASSUMPTIONS

1. The ground water zone is infinite in aerial extent.
2. The zone is homogeneous, isotropic, and of uniform thickness over the area influenced by the test.
3. Prior to pumping, the piezometric surface is horizontal, or nearly so, over the area to be influenced.
4. The well penetrates the entire ground water zone and, thus, receives water by horizontal flow.
5. The water removed from storage is discharged instantaneously with decline of head.
6. Non-linear well losses are negligible.

The following assumptions/conditions apply to leaky confined ground water zones.

1. The aquitard is infinite in aerial extent.
2. The aquitard is homogeneous, isotropic and of uniform thickness.
3. The water supplied by leakage from the aquitard is discharged instantaneously with decline in head.

METHOD	APPLICATION		REMARKS
	Ground Water Zone Type	Flow Condition	
Papadopulos and Cooper (1967) (a & b)	Confined	Transient	Early time data does not adequately reflect zone characteristics May be difficult to match the data curve with appropriate type curves because of similarities of curves Constant discharge Equations take storage capacity of well into account
Rushton and Singh (1983) (b)	Confined	Transient	More sensitive curve fitting than Papadopulos and Cooper method Constant discharge
Birsoy and Summers(1980) (b)	Confined	Transient	Variable discharge (zone is pumped stepwise or is intermittently pumped at constant discharge)
Hurr-Worthington (Worthington, 1981) (b)	Confined or leaky confined	Transient	Constant discharge Modified Theis Equation
Jacob's Straight Line Method (b)	Confined or leaky confined	Transient	Sensitive to minor variations in discharge rate May be able to account for partial penetration if late-time data is used Constant discharge
Hantush (1959b) (b)	Leaky confined/ artesian	Transient	Flow through aquitard is vertical Variable discharge
Jacob and Lohman (1952)(b)	Confined/ artesian	Transient	If value of the effective radius is not known then storativity cannot be determined Variable discharge (drawdown is constant)

a-Described in Dawson and Istok (1991), b-Described in Kruseman and de Ridder (1990)

MULTIPLE WELL PUMPING TESTS

A multiple well test is implemented by pumping a well continuously and measuring water level changes in both the pumped and observation wells during pumping or subsequent recovery. Properly designed and conducted multiple well tests can be used to define the overall hydrogeologic regime of the area being investigated, including T, S and/or specific yield of a zone. They also can help design municipal well fields, predict rates of ground water flow, determine interconnectivity between ground water zones, and design a remediation system.

Two basic types of multiple well pumping tests are constant discharge and variable discharge. The former is performed by pumping at a constant rate for the duration of the test, while the latter is distinguished by changes in rate. Measurements obtained from the pumping well generally are less desirable for calculating hydraulic properties because of the irregularities induced from the operation of the pump and well bore storage. Obtaining data from observation well(s) allows for characterization of the pumped zone over a larger area.

Test design and data analysis depends on the characteristics of the zone tested, the desired/required information to be evaluated, and available funds. Design and analysis are summarized below. More detailed information can be found in Lohman (1972), Walton (1987), Dawson and Istok (1991), and Kruseman and de Ridder (1990).

PRELIMINARY STUDIES

Pumping test methods are specific to the hydrogeology of the area being evaluated and the specific assumptions of the analytical solution of the chosen test method. Therefore, a prerequisite for selecting the most appropriate method is gathering as much information about the site as possible. Prior to testing, the following should be gathered:

- Geologic characteristics of the subsurface that may influence ground water flow.
- Type of water-bearing zone and its lateral and vertical extent.
- Depth, thickness, and lateral extent of any confining beds.
- Location of recharge and discharge boundaries.
- Horizontal and vertical flow components (e.g., direction, gradient).
- Location, construction, and zone of completion of any existing wells in the area.
- Location and effects of any pumping wells.
- Approximate values and spatial variation of formation K, T and S.
- Seasonal ground water fluctuations and any regional trends.

This preliminary information can assist in the proper design of the test and the choice of a conceptual model. Test design also can be facilitated by preliminary conceptual modeling to predict the outcome of the test beforehand (Walton, 1987). This serves two purposes. First, it describes the ground water zone so that an appropriate data analysis method is evident. Second, it suggests deficiencies in observation well locations.

Costs frequently are reduced by using existing wells (production, drinking, monitoring) rather than installing new ones. However, they need to be evaluated to determine whether they are properly constructed, located and equipped to be used for pumping and/or observation points. Single well tests should be conducted on the existing wells to determine whether they will respond to water level changes.

PUMPING TEST DESIGN

As indicated, the design of a pumping test depends on the hydrogeologic environment and the purpose of the test. The designer should determine pumping well location (areal and depth) and design, pumping rate, pump selection, location and depth of observation wells, test duration, discharge rate measurements and devices, interval and method of water level measurements, and method of analyzing data.

Pumping Well Location

A pumping well should be located far enough away from hydraulic boundaries to permit recognition of drawdown trends before boundary conditions influence the data (Sevee, 2006). To minimize the effect of stream, river or lake bed infiltration, it should be located at a distance equal to or exceeding the ground water zone thickness from the possible boundary (Walton, 1987). However, if the intent is to induce recharge, then the pumping well should be located as close to the boundary as possible (Sevee, 2006). The appropriate depth should be determined from exploratory boreholes or logs from nearby wells.

Pumping Well Design

The design of a pumping well depends on the hydrogeologic environment, the choice of conceptual model, and economics. Components to consider include diameter, length and depth of the screened interval, and screen slot configuration.

A general rule is to screen the well over at least 80 percent of the ground water zone thickness. This makes it possible to obtain about 90 percent or more of the maximum yield that could be obtained if the entire zone were screened, and also allows horizontal flow toward the well to be assumed, which is an assumption that underlies almost all well-flow equations. Pumping wells completed in thick zones often have intake lengths less than 80 percent of the thickness. These wells are considered partially penetrating (Kruseman and de Ridder, 1990), and pumping would be expected to induce vertical flow components. As a result, corrections to the drawdown data may be necessary. Corrections are discussed later in this chapter.

The diameter of a pumping well depends on the method chosen to analyze the data and the estimated hydraulic properties. It must accommodate the pump, assure hydraulic efficiency, and allow measurement of depth to water before, during and after pumping. Table 4.3 recommends casing diameters based on pumping rates; however, the final selection should be based on consultation with the pump manufacturer.

The screen slot size and filter pack material should be based on the grain size distribution of the zone being pumped (Kruseman and de Ridder, 1990). The screen should be factory slotted or perforated over no more than 30 to 40% of its circumference. Slots should be long and narrow or continuous. Slots produced manually are not appropriate under any circumstances.

Table 4.3 Recommended pumping well diameter for various pumping rates. **(Dawson and Istok, 1991, after Driscoll, 1986).**

PUMPING RATE		***DIAMETER***	
gal/min	***m^3/day***	***(in)***	***(mm)***
<100	<545	6	152
75-175	409-954	8	203
150-350	818-1910	10	254
300-700	1640-3820	12	305
500-1000	2730-5450	14	365
800-1800	4360-9810	16	406
1200-3000	6540-16400	20	508

Pumping Rate

The rate(s) should be sufficient to ensure that the ground water zone is stressed and that drawdown can be measured accurately. The water table in an unconfined zone should not be lowered by more than 25 percent. This is the largest drawdown that can be corrected and analyzed with an analytical solution of the ground water flow equation (Dawson and Istok, 1991). The pumping rate for tests conducted in confined zones should not readily dewater the pumping well. Well efficiency and an appropriate pumping rate for a constant discharge test can be determined by conducting a step-drawdown test (See Single Well Tests)

Other methods that may be useful to estimate an appropriate pumping rate include: 1) using an empirical formula to predict well specific capacity, and 2) predicting drawdown using analytical solutions. These methods are described by Dawson and Istok (1991). It should be noted that these techniques predict discharge rates that can be utilized to determine hydraulic parameters and should not be utilized to estimate an appropriate rate for capturing a contaminant plume.

Pump Selection

The pump and power supply must be capable of operating continuously at an appropriate constant discharge rate for at least the expected duration of the test. Pumps powered by electric motors produce the most constant discharge (Stallman, 1983).

Observation Well Number

The appropriate number of observation wells depends on the goals of the test, hydrogeologic complexity, the degree of accuracy needed, and the method employed to analyze the data. In general, at least three are recommended (Kruseman and de Ridder, 1990). If two or more are available, data can be analyzed by both time (x-axis) versus drawdown (y-axis) and distance (x-axis) versus drawdown (y-axis) relationships. Using both and observing how wells respond in various locations provides greater assurance that: 1) the calculated hydraulic properties are representative of the zone being pumped over a large area, and 2) any heterogeneities that may affect the flow of ground water and contaminants have been identified. In areas in where several complex boundaries exist, additional wells may be needed to allow proper interpretation of the test data (Sevee, 2006).

Observation Well Design

In general, observation wells need to be constructed with an appropriate filter pack, screen slot size, and annular seal, and must be developed properly. Practices for design and development of observation wells can be similar to those for monitoring wells (see TGM Chapters 7 & 8). The observation wells/piezometers should be of sufficient diameter to accommodate the measuring device, but should not be so large that the drawdown cannot be measured.

Observation Well Depth

Fully-penetrating wells are desirable. The open portion of an observation well generally should be placed the same horizon as the intake of the pumping well. When testing heterogeneous zones, it is recommended that an observation well be installed in each permeable layer. Additional wells should be placed in aquitards to determine leakage and interconnectivity (Kruseman and de Ridder, 1990).

Observation Well Location

Observation well location depends on the type of ground water zone, estimated transmissivity, duration of the test, discharge rate, length of the pumping well screen, whether the zone is stratified or fractured, and anticipated boundary conditions. Placing observation wells 10 to 100 meters (33 to 328 feet) from the pumping well is generally adequate for determining hydraulic parameters. For thick or stratified, confined zones, the distance should be greater (Kruseman and de Ridder, 1990). Also, additional observation wells should be located outside the zone of influence of the pumping well to monitor possible natural changes in head.

In general, observation wells completed in a confined ground water zone can be spaced further from the pumping well than those completed in an unconfined zone. The decline in the piezometric surface of confined zones spreads rapidly because the release of water from storage is entirely due to compressibility of water and the ground water zone material. Water movement in unconfined zones is principally from draining of pores, which results in a slower expansion.

Under isotropic conditions, the distribution of the observation wells around the pumping well can be arbitrary. However, an even distribution is desirable so that drawdown measurements represent the largest volume as possible (Dawson and Istok, 1991). If feasible, at least three wells should be logarithmically spaced to provide at least one logarithmic cycle of distance-drawdown data (Walton, 1987). If anisotropic conditions exist or are suspected, then a single row of observation wells is not sufficient to estimate the directional dependence of transmissivity. A minimum of 3 observation wells, none of which are on the same radial arc, is required to separate the anisotropic behavior.

The length of the pumping well screen can have a strong influence on the distance of the observation wells from the pumping well. Partially-penetrating pumping wells will induce vertical flow, which is most noticeable near the well As a result, water level measurements taken from these wells need to be corrected; however, the effects of vertical flow become more negligible at increasing distances from the pumping well. For partially penetrating pumping wells, corrections to the drawdown data may not be necessary if the following relation holds true (Sevee, 2006; and Dawson and Istok, 1991):

$$MD \geq 1.5D\sqrt{\frac{K_H}{K_v}}$$

M.D. = minimum distance between pumping well and observation well.
D = saturated thickness.
K_H = horizontal K and K_V = vertical K.

Drawdown measured in observation wells located less than the minimum distance should be corrected. Typically, horizontal K is ten times greater than vertical K. If this ratio is used, then the minimum distance becomes 1.5D/10. Note that partially penetrating wells located at or greater than the minimum distance may be too far away to show drawdown.

Anticipated boundary conditions (e.g., an impervious zone or a recharging river) also can affect the placement of observation wells. Wells should be placed to either minimize the effect of the boundary or more precisely locate the discontinuity (Dawson and Istok, 1991). According to Walton (1987), to minimize the effect of the boundary on distance-drawdown data, wells should be placed along a line through the pumping well and parallel to the boundary. Observation wells also should be placed on a line perpendicular to the boundary. If more than one boundary is suspected or known, the wells should be located so that the effects on drawdown data encountered by the first boundary have stabilized prior to encountering the second boundary (Sevee, 2006).

Observation points in nearby surface water bodies can be monitored to help determine if interconnection exists between the ground water and surface water.

Duration of Pumping

The appropriate duration of a pumping test depends on the hydrogeologic setting, boundary conditions, degree of accuracy desired, and objectives of the test. In general, longer tests are needed to address boundary conditions; while shorter tests may be acceptable to determine hydraulic parameters. Economic factors and time constraints also may be influential; however, economizing the period of pumping is not recommended. The cost of continuing a test is low compared to total costs, particularly when the wells have been specially constructed and positioned for test purposes (Kruseman and de Ridder, 1990).

Pumping tests commonly last from five hours to five days (Walton, 1962). In some cases, tests may need to be continued until the cone of depression has stabilized and does not expand as pumping continues (e.g., drawdown does not appreciably increase/decrease). Such a steady state or equilibrium can occur within a few hours to weeks or never. According to Kruseman and de Ridder (1990), the average time to reach steady state a leaking ground water zone is 15 to 20 hours. A test of a confined ground water zone should last a minimum of 24 hours. Three days or more should be allowed for tests conducted in unconfined zones because of the slow expansion of the cone of depression. The duration necessary to define the hydraulic parameters depends on the regional and local geologic/hydrogeologic setting. Plotting drawdown data during tests often reveals anomalies and the presence of suspected or unknown boundaries, and assists in determining test duration.

Discharge Rate Measurement

Variation in discharge rates produces aberrations in drawdown that are difficult to treat in data analysis. Engines, even those equipped with automatic speed controls, can produce variations up to 20 to 25 percent over the course of a day. The rate should never vary by more than five percent (Osborne, 1993). To obtain reliable data, discharge should be monitored and adjustments made as needed.

The frequency of measurements depends on the pump, engine power characteristics, the well, and the zone tested. Discharge from electric pumps should be measured and adjusted (if necessary) at 5, 10, 20, 30, 60 minutes, and hourly thereafter. Other types of pumps may require more frequent attention; however, no "rule of thumb" can be set because of the wide variation in equipment response (Stallman, 1983).

Discharge Measuring Devices

Some discharge measurement techniques are more accurate than others and some allow for a convenient means of adjusting rate. A ***commercial water meter*** of appropriate capacity can be utilized. It should be connected to the discharge pipe in a way that ensures accurate readings. A disadvantage is the unavoidable delay in obtaining values at the start of the test, when pumping rate is being adjusted to the desired level (Driscoll, 1986). When discharge is low, the rate can be measured as a function of time to fill a ***container of known volume***. The ***orifice weir*** is commonly used to measure discharge from high capacity pumps. A manometer is fitted into the discharge pipe. The water level in the manometer represents the pressure in the pipe when the water flows through the orifice. Details on orifice design and interpretation of results can be found in Driscoll (1986). Finally, discharge rate can be obtained by water level measurements taken from ***weirs and flumes***. The rate of flow is determined within known constriction dimensions placed in the discharge channel originating at the well head (Driscoll, 1986).

Interval of Water Level Measurements

Pre-test Measurements

Prior to the start of tests, water level data should be collected from the pumping and observation wells to determine existing trends for all zones to be monitored. The pumping phase should begin only if identified and recorded trends are expected to remain constant. As a general rule, the period of observation should be at least twice the length of the estimated time of pumping (Stallman, 1983). Water levels should be measured and recorded hourly for all zones. In addition, the barometric pressure should be monitored, at least hourly, to determine the barometric efficiency of ground water zone(s), which may be useful in correcting the drawdown data. Barometric efficiency is discussed later in this chapter.

Measurements During Pumping

The appropriate time interval for water level measurements varies from frequent at the beginning of a test, when water-levels are changing rapidly, to long at the end of the test, when change is slow. Typical intervals for the pumping well and observation wells located close to the pumping well are given in Tables 4.4 and 4.5, respectively. Though specified intervals need not be followed rigidly, each logarithmic cycle should contain at least 10 data points spread through the cycle (Stallman, 1983). Frequent readings are essential during the first hour since drawdown occurs at a faster rate in the early time interval. For wells further away and those located in zones above or below the pumping zone, the frequent measurements recommended by Table 4.5 for the first few minutes of the pumping tests are less important (Kruseman and de Ridder, 1990).

Table 4.4 Range of interval between water-level measurements in the pumping well (Kruseman and de Ridder, 1990).

TIME SINCE START OF PUMPING	TIME INTERVAL
0 to 5 minutes	0.5 minutes
2 to 60 minutes	5 minutes
60 to 120 minutes	20 minutes
120 to shutdown of the pump	60 minutes

Table 4.5 Range of intervals between water-level measurements in observation wells (Kruseman and de Ridder, 1990).

TIME SINCE START OF PUMPING	TIME INTERVAL
0 to 2 minutes	approx. 10 seconds
2 to 5 minutes	30 seconds
5 to 15 minutes	1 minute
50 to 100 minutes	5 minutes
100 minutes to 5 hours	30 minutes
5 hours to 48 hours	60 minutes
48 hours to 6 days	3 times a day
6 days to shutdown of the pump	1 time a day

According to Stallman (1983), it is not necessary to measure water levels in all wells simultaneously, but it is highly desirable to achieve nearly uniform separation of plotted drawdowns on a logarithmic scale. All watches used should be synchronized before the test is started, and provisions made to notify all participants at the instant the test is initiated.

Measurements During Recovery

After pumping is completed, water level recovery should be monitored with the same frequency used during pumping. Measurements should commence immediately upon pump shut down and continue for the same duration as the pumping phase, or until the water levels have reached 95 percent of the initial, pre-pumping static water level. A check valve should be used to prevent backflow of water in the riser pipe into the well, which could result in unreliable recovery data.

Water Level Measurement Devices

The most accurate recording of water level changes is made with fully automatic microcomputer-controlled systems that use pressure or acoustic transducers for continuous measurements. Water levels can also be determined by hand, but the instant of each reading must be recorded with a chronometer. Measurements can be performed with floating steel tape equipped with a standard pointer, electronic sounder, or wet-tape method. For observation wells close to the pumped well, automatic recorders programmed for frequent measurements are most convenient because water level change is rapid during the first hour of the test. For detailed descriptions of automatic recorders, mechanical and electric sounders, and other tools, see Driscoll (1986), Dalton et al. (2006), and ASTM D4750-87(2001). Chapter 10 of this document contains a summary of manual devices.

The measurement procedure should be standardized and the instrument calibrated prior to the start of the test. Transducers should be calibrated by a direct method, and the calibration should be checked at the conclusion of the recovery test.

Discharge of Pumped Water

Water extracted during a pumping test must be discharged properly and in accordance with any applicable laws and regulations. At sites with contaminated ground water, the discharge may need to be containerized and sampled to assess the presence of contaminants and, if necessary, treated and/or disposed at an appropriate permitted facility.

It is not the intent of this document to define Ohio EPA policy on disposal of pumped water. In general, the water should be evaluated to determine if it is characteristically a waste. If the ground water has been contaminated by a listed hazardous waste, the ground water is considered to "contain" that waste, and must therefore be managed as such. Disposal must be at a permitted hazardous waste facility. Treatment must be in a wastewater treatment system that is appropriate for the waste and meets the definitions contained in OAC rule 3745-50-10.

If containerization is not necessary, then pumped water must be discharged in a manner that prevents recharge into any zone being monitored during the test. At a minimum, the water should be discharged 100 to 200 meters from the pumped well. This is particularly important when testing unconfined zones. At no time should the discharge water be injected back into the subsurface. A permit for discharge via stream or storm sewer may be required (contact the Division of Surface Water, Ohio EPA).

Decontamination of Equipment

Decontamination of equipment is important throughout an in-situ test. Contact of contaminated equipment with ground water (or a well) may cause a measuring point to be unsuitable for water quality investigations. Details on appropriate methods can be found in Chapter 10.

CORRECTION TO DRAWDOWN DATA

Prior to using the drawdown data collected from a pumping test, it may be necessary to correct for either external sources or effects induced by the test. Barometric pressure changes, tidal or river fluctuations, natural recharge and discharge, and unique situations (e.g., a heavy rainfall) may all exert an influence. In confined and leaky ground water zones, changes in hydraulic head may be due to influences of tidal or river-level fluctuations, surface loading, or changes in atmospheric pressure.

Diurnal fluctuations in water levels can occur in unconfined zones due to the differences between night and day evapotranspiration. Corrections to measurements may be needed for unconfined ground water zone data due to a decrease in saturated thickness caused by the pumping test. Also, corrections may be necessary if the pumping well partially penetrates the zone tested. By identifying pre-test water level trends in zone(s) of interest, long and short-term variations can be eliminated from the data if their impacts are significant during the pumping phase (Figure 4.3).

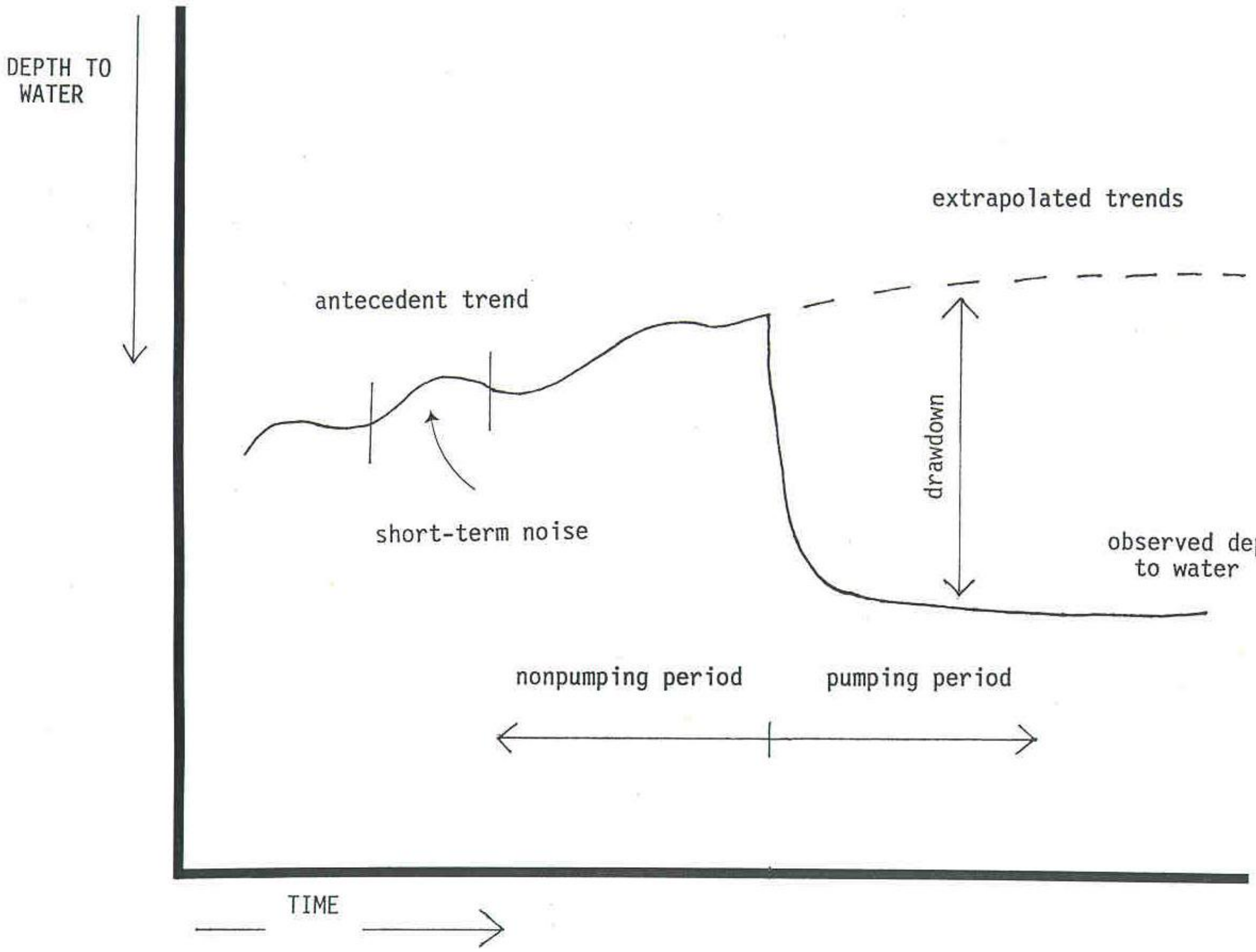

Figure 4.3 Hydrograph for hypothetical observation well showing definition of drawdown (adapted from Stallman, 1983).

To determine if corrections are necessary, measurements should be taken during the test in observation wells unaffected by the pumping. Hydrographs of the pumping and observation wells covering a sufficient period of pre-test and post-recovery periods can help determine if the data needs to be corrected and also to correct the drawdown data. If the same constant water level is observed during the pre-testing and post-recovery periods, it can safely be assumed that no external events exerted an influence (Kruseman and de Ridder, 1990).

Barometric Pressure

Data for confined and leaky zones needs to be corrected for the amount of rise in water levels resulting from a decrease in atmospheric pressure and/or the amount of fall resulting from an increase. To make the correction, the barometric efficiency (BE) of the zone needs to be determined. The BE can be calculated by the following equation [Dawson and Istok (1991) and Kruseman and de Ridder (1990)]:

$$BE = \frac{\partial h}{\partial \rho / Y_w} \times 100\%$$

where: Mh = change of head in the observation well.
(MΔK$_w$) = change in atmospheric pressure expressed as a height of water.
Δ_a = change in atmospheric pressure.
Y_w = specific weight of water.

If the change in hydraulic head is plotted versus the change in pressure (measured column height) and a best-fit straight line is drawn, then the slope of the line is the BE. From changes in atmospheric pressure observed during the test and the BE, the change in water level due to changes in barometric pressure can be calculated and the drawdown data can be corrected. When artesian zones are tested, barometric pressure (to a sensitivity of +/- 0.01 inch of mercury) should be recorded continuously throughout the testing period. Barometric efficiency typically ranges between 0.20 and 0.75 (Kruseman and de Ridder, 1990).

Saturated Thickness

The saturated thickness of an unconfined zone decreases during pumping tests; however, most conceptual models are based on the assumption that it remains constant. This assumption can be accepted if the saturated thickness does not decrease more than 25 percent. If the decrease is greater then 25 percent, then the drawdown data should be corrected prior to analysis (Dawson and Istok, 1991).

According to Jacob (1944), data for unconfined zones can be corrected for saturated thickness change with the following equation:

$$S_{corrected} = s - s^2 / 2m$$

where: $s_{corrected}$ = corrected drawdown

m = initial saturated thickness.

However, this correction is based on the Dupuit-Forchheimer assumption (ground water flows horizontally and hydraulic gradient is equal to the slope of the water table). Neuman (1975) showed that this assumption is not valid for an unconfined until the later portion of the test when the drawdown matches the Theis type curve. Therefore, the correction is not recommended with early and intermediate data (Dawson and Istok, 1991).

Unique Fluctuations

Data cannot be corrected for unique events such as a heavy rain or sudden fall or rise of a nearby river that is hydraulically connected to the zone tested. However, in favorable circumstances, some allowances can be made for the resulting fluctuations by extrapolating data from a controlled piezometer outside the zone of influence. In most cases, the data collected is rendered worthless and the test has to be repeated when the situation returns to normal (Kruseman and de Ridder, 1990). It is also important to understand the effects of nearby industrial or municipal pumping wells prior to conducting a pumping test. Also, it may be necessary to monitor/evaluate the effects of surficial loading (e.g., passing trains) on water level measurements.

Partially Penetrating Wells

In some cases, a ground water zone is so thick that it is not justifiable to install a fully-penetrating well, and the zone must be pumped by a partially-penetrating well. Partial-penetration causes vertical flow in the vicinity of the well, which results in additional head loss. As indicated earlier, this effect decreases with increasing distance from the pumping well and no correction is necessary if the observation well is at a distance greater than 1.5 $D/K_H/K_V$. Various methods have been developed to correct data for the effects of partially penetrating wells. These were discussed in detail by Kruseman and de Ridder (1990). Table 4.6 lists the methods and their general applications.

Noordbergum Effect

The Noordbergum effect (also called the Mandel-Cryer effect) is observed in observation wells monitored in an upper or lower zones above the pumping zone. A rise in water levels may occur in these units due to compression of the aquitard and an increase in pore pressure or, equivalently, a hydraulic buildup (instead of the expected drawdown). The effects generally occur early and die with time. See Sara (2003) for additional explanation.

ANALYSIS OF MULTIPLE WELL PUMPING TEST DATA

Many methods (e.g., Theis, Cooper-Jacob, etc.) and computer software programs exist for interpreting multiple well pumping test data. The hydraulic properties computed by a particular method can only be considered correct if the assumptions included in the conceptual model on which the method is based are valid for the particular system being tested. Because the computed values depend on the choice of conceptual model used to analyze the data, the selection of an appropriate model is the single most important step in analysis (Dawson and Istok, 1991).

It is beyond the scope of this document to detail or discuss the various models. Tables 4.7 through 4.11 can be used for a preliminary selection of a method. In addition, ASTM Method D4043-96(2004) provides a decision tree for the selection of a test method and ASTM Methods D4106-96(2004) and D4105-96(2002 offer information on determining hydraulic parameters. In addition to ASTM standards, information on aquifer analysis conceptual models and/or programs can be found in: Batu (1998) Dawson and Istok (1991), and Kruseman and de Ridder (2000).

Data collected during a pumping test are subject to a variety of circumstances that may be recognized in the field or may not be apparent until data analysis has begun. In either case, all information (including field observations) must be examined during data correlation and analysis.

Table 4.6 Corrections for partially penetrating effects (information derived from Kruseman & de Ridder, 1990.)

METHOD	***APPLICATION***	***ORIGINAL SOURCE***
Huisman Method I	- confined - steady state	Anonymous, 1964
Huisman Method II	- confined - unsteady state - time of pumping relatively short	Hantush (1961 a, 1961 b)
Hantush Modification of Theis Method	- confined - unsteady state - time of pumping relatively short	Hantush (1961 a, 1961 b)
Hantush, Modification of Jacob Method	- confined - unsteady state - time of pumping relatively long	Hantush (1961 b)
Weeks', "Modification of Walton and the Hantush Curve Fitting Methods"	- leaky - steady state flow	Weeks (1969)
Streltsova's Curve Fitting Method	- unconfined - anisotropic - unsteady state	Streltsova (1974)
Neuman's Curve-Fitting Method	- unconfined - anisotropic	Neuman (1974, 1975, 1979)

PRESENTATION OF MULTIPLE WELL TESTS DATA

The guidelines below recommend the minimum criteria for how multiple well test data should be compiled, presented, and summarized to document that the hydraulic properties of the zone(s) of interest have been adequately determined.

- Preliminary evaluation of hydrogeologic conditions, including all data used to plan and design the test.

- Summary of the design and implementation of the pumping tests including, but not limited to:

Geologic zone into which the pumping well is completed (i.e. areal extent, thickness, lateral and vertical extent).

Pumping well construction (justification should be provided if the well screen is partially penetrating).

Duration of pumping.

Rate of pumping and method for determination.

Location of all observation wells.
Geologic zone(s) to be monitored (including depths, thickness, spatial relationship to the pumped zone).

Observation and pumping well construction.

Method of water level measurements (for each well).

Methods for gathering data used to correct drawdown and establishment of existing trends in water levels.

Procedures for the discharge and disposal (if necessary) of pumped water.

Date and time pumping began and ended.

$ Raw data, including water level measurements, time of measurement in minutes after pumping started or ended, drawdown, pumping rates, etc. should be included in tabular form. All data should be expressed in consistent units. Water level in nearby surface water bodies should also be provided, if taken. If the data set is large, it may be provided on disk.

• Data plots and type curves. All graphs and data plots should be labeled clearly.

Data plots of (e.g., drawdown versus time) should be presented for the pumping well and each observation well on double-logarithmic and semi-logarithmic paper. Time data (in minutes) should be depicted along the horizontal axis, and drawdown should be depicted along the vertical axis. For semi-logarithmic plots, drawdown should be presented along the vertical arithmetic axis.

The horizontal scale should be the same for all data plots.

All data points on the plots should be clearly labeled. In the event that data from multiple wells are presented on the same plot, the labeling should be distinct so as to enable differentiation between sets of data, and be identified in a legend.

Data plots of drawdown versus distance from the pumping well should be presented; calculations of hydraulic properties based on these plots should be used to corroborate calculations made from time drawdown data plots. Data plots of residual drawdown versus time since pumping stopped should be presented for recovery data.

Data plots of discharge rate versus time should be presented.

For data depicted on double-logarithmic plots, the following requirements should be met: If a single type curve has been used to analyze the data, the type curve should be presented directly on the data plot.

If an analysis method employing a family of type curves has been used, all curves selected to fit the data (including both early and late time responses to pumping, if applicable) should be depicted directly on the data plot, and a discussion addressing the applicability of using multiple type curves should be included in the site investigation report.

Match point values should be identified on data plots.

For data depicted on semi-logarithmic plots, the portion of the data to which a straight line is fit should be indicated on the plot.

- Calculations. Equations used for calculating hydraulic properties should also be included in the report.

- In the event that any boundaries are encountered by the cone of depression during the test, the report should contain (1) a reference to the data plot on which the boundary's impact can be observed, (2) identification of the type of boundary, and (3) a discussion addressing the boundary's effect on the hydraulics at the site. For pumping wells, an evaluation of casing storage effects should be included

- Comments noting any external events (e.g., change in weather patterns, passage of train or heavy machinery). In the event that drawdown data need adjustment due to external effects or reduction in saturated thickness, separate data plots depicting both adjusted and unadjusted drawdown versus time and versus distance should be presented for the appropriate wells. Any plots, graphs, or equations used to determine the magnitude of drawdown adjustment should also be presented.

. • Data analysis method and/or programs, including assumptions, limitations and their applicability to the site.

- In the event that a computer program is used to perform the analysis, only those software programs that provide analysis of the data based on graphical curve matching, rather than least-squares analysis, and allow for the generation of data plots should be used.

- Interpretation of the data using both results of the test and other available hydrogeologic information.

RECOVERY TESTS

Recovery tests (also called residual drawdown tests) involve measuring water level rise after the pump is shut down. These tests provide an independent check on the transmissivity and storativity determined from a pumping test. The results should be used in conjunction with calculations obtained from the pumping phase to estimate the true hydraulic properties of the zone(s) of interest. Results of a recovery test can be more reliable than pumping test results because recovery is not influenced by the erratic fluctuations that can be characteristic of pumping.

As with the early portions of the pumping phase in which water levels drop rapidly, water levels rise rapidly during early portions of the recovery phase and are followed by a decreasing rate of water level rise. It is therefore important to establish the same schedule for obtaining water level measurements during the initial portions of the recovery phase as that used during the pumping phase (Kruseman and de Ridder, 1990. Table 4.12 provides methods for analyzing recovery data.

At a minimum, the following information should be provided: date and time the pumping phase ended and the recovery phase began, initial and final water levels for the recovery phase, time since pumping stopped (in minutes), measured water level, residual drawdown, and records of any noteworthy occurrences.

Table 4.7 Multiple-well, constant discharge pumping tests, unconfined ~~aquifer~~ ground water zone.

GENERAL ASSUMPTIONS

1. The ground water zone is unconfined and bounded below by an aquiclude.
2. All layers are horizontal and extend infinitely in the radial extent.
3. The ground water zone is homogeneous, isotropic (unless noted) and of uniform thickness~~.~~
4. Prior to pumping, the water table is horizontal over the area that will be influenced by the test.
5. Ground water density and viscosity are constant.
6. Ground water flow can be described by Darcy's Law.
7. Head losses through well screen and pump intake are negligible.
8. The ground water zone is compressible and completely elastic.
9. The zone has been pumped long enough that equilibrium has been reached.
10. Drawdown is small compared to the saturated thickness (i.e., no more than 25 percent).
11. Pumping and observation wells are screened over the entire saturated thickness (unless noted).
12. Ground water flow above the water table is negligible.

METHOD	CAN ACCOUNT FOR			REMARKS
	Flow Conditions	Partial Penetration	Other	
Neuman's Curve Fitting Method (Neuman, 1972) (a,b)	Transient	No	anisotropic conditions	Theory should be valid for piezometers with short screens provided that the drawdowns are averaged over the saturated thickness (Van der Kamp, 1985)
Thiem-Dupuit's Method, (Thiem, 1906) (b)	Steady state	No		Steady state will only be achieved after long pumping time Does not give accurate description of drawdown near the well Assumptions ignore the existence of a seepage face at the well and the influence of the vertical velocity component
Boulton and Streltsova (1976) a	Transient	Yes	storage in the well anisotropy	
Neuman (1974) a	Transient	Yes	anisotropy	

a Described in Dawson and Istok, 1991

b Described in Kruseman and de Ridder, 1990

t = time, I = transmissivity, r = radial distance from the pumping well, r_w = effective radius of the pumping well, r_c= inside radius of the pumping well within the range of water fluctuations

Table 4.8 Multiple-well, constant-discharge pumping tests, confined ground water zones.

GENERAL ASSUMPTIONS

1. The ground water zone is confined and bounded above and below by aquicludes.
2. The ground water zone is homogeneous, isotropic (unless noted in special conditions) and of uniform thickness over the area influenced by the test.
3. All layers are horizontal and extend infinitely in the radial extent.
4. Prior to pumping, the piezometric surface is horizontal and extends infinitely in the radial direction.
5. Ground water density and viscosity are constant.
6. Ground water can be described by Darcy's Law.
7. Head losses through well screen and pump intake are negligible.
8. Ground water flow is horizontal and is directed radially to the well.
9. Pumping well and observation wells are screened over the entire thickness of the ground water zone.

Additional assumptions for unsteady state flow.

10. The water removed from storage is discharged instantaneously with decline of head.
11. The diameter of the well is small, i.e., the storage in the well can be neglected.

METHOD	APPLICATION			REMARKS
	CAN ACCOUNT FOR			
	Flow Conditions	**Partial Penetration**	**Other**	
Thiem (1906) (a,b)	Steady state	No		Equation should be used with caution and only when other methods cannot be applied Drawdown is influenced by well losses, screen and pump intake
Theis (1935) (a,b)	Transient	No		Because there may be a time lag between pressure decline and release of stored water, early drawdown data may not closely represent theoretical drawdown data
Hantush (1964) (b)	Transient	Yes	Anisotropy in the horizontal plane	Inflection point method can be used when the horizontal and vertical hydraulic conductivities can be reasonably estimated.
Jacob's Method (Cooper and Jacob, 1946) (b)	Transient	No		Can also be applied to single well pump tests Condition that u values are small usually is satisfied at moderate distances from the well within a hour or so. at $u < 0.05$ or 0.10, error introduced is 2 and 5% respectively Based on Theis Equation, straight line method based on drawdown versus time on semi-log paper

Table 4.8 (continued): Multiple-well, constant discharge pumping tests, confined.

METHOD	APPLICATION — CAN ACCOUNT FOR: Flow Conditions	Partial Penetration	Other	REMARKS
Weeks (1969) (b)	Transient	Yes	Anisotropy in the vertical plane	Similar procedure can be applied to leaky ground water zones
Papadopulos (1965) (a)	Transient	No	Anisotropy in horizontal plane	Minimum of three observation wells
Papadopulos and Cooper (1967) (a)	Transient	No	Well Storage	Pumping rate is the sum of the ground water entering in the pumping well from the zone and the rate of decrease of water stored in well casing.
Neuman's Extension of Papadopulos (Neuman et al., 1984) (b)	Transient	No	Anisotropy in the horizontal plane	More reliable results can be obtained by conducting 3 pumping tests. The zone is penetrated by at least three wells, which are not on the same ray.
Hantush (1966) (b)	Transient	No	Anisotropy in the horizontal plane	If the principal direction of anisotropy is known, drawdown data from two piezometers on different rays is sufficient. If not, 3 wells on different rays will be needed. Use of Theis (1906) or Cooper and Jacob (1946)
Hantush and Thomas (1966) (b)	Transient	No	Anisotropy in the horizontal plane	Apply methods for confined isotropic ground water zones to the data for each ray of piezometers

a Described in Dawson and Istok (1991)
b Described in Kruseman and de Ridder (1990)

Table 4.9 Multiple-well, Constant discharge pumping tests, leaky ground water zones.

GENERAL ASSUMPTIONS

1. The ground water zone is leaky.
2. The ground water zone and aquitard have seemingly infinite and areal extent.
3. The ground water zone and aquitard are homogeneous, isotropic (unless noted), and of uniform thickness over the area influenced by the test.
4. Prior to pumping, the piezometric surface and the water table are horizontal over the area that will be influenced by the test.
5. The well penetrates the entire thickness of the zone and thus receives water by horizontal flow (unless noted).
6. The flow in the aquitard is vertical.
7. The drawdown in the unpumped ground water zone (or aquitard) is negligible.
8. Ground water flow can be described by Darcy's Law.

Additional assumptions for transient conditions:

9. Water removed from storage and the water supplied by leakage from the aquitard is discharged instantaneously with decline of head.
10. The diameter of the well is very small, i.e., the storage in the well can be neglected.

METHOD	CAN ACCOUNT FOR			REMARKS
	Flow conditions	Partial Penetration	Other	
De Glee (1930 & 1951) (b)	steady state	No		
Hantush (1960) (b)	Transient	No	Takes into account storage changes in the aquitard	Only the early-time drawdown should be used to satisfy the assumption that the drawdown in the aquitard is negligible Generally is Theis equation plus an error function
Hantush-Inflection Point (1956) (a,b)	Transient	No		Accuracy depends on accuracy of extrapolating the maximum drawdown Two different methods, one requires one piezometer, and the other requires data from two piezometers
Hantush-Jacob (1955) (b)	Steady state	No		
Lai and Su (1974) (a,b)	Transient	No		
Neuman-Witherspoon (1972) (b)	Transient	No		Need to calculate transmissivity using one of the other methods

Table 4.9 (continued). Multiple-well, constant discharge, pumping tests, leaky.

METHOD	CAN ACCOUNT FOR			REMARKS
	Flow conditions	Partial Penetration	Other	
Hantush-Jacob (1955) (a)	Transient	No		Drawdown in the source bed can be neglected when KD of source bed is >100 KD of ground water zone Ground water zone is bounded above by aquitard and an unconfined ground water zone and bounded below by an aquiclude Ground water flow in the aquitard is vertical
Walton (1962) (b)	Transient	No		To obtain the unique fitting position of the data plot with one of the type curves, enough of the observation data should fall within the period when leakage effects are negligible
Hantush (1966) (b)	Transient	No	Anisotropic in horizontal plane	Similar to Hantush's methods for confined zone except initial step uses methods to calculate the hydraulic parameters
Weeks (1969) (b)	Transient	Yes	Anisotropic in the vertical plane	Similar process can be conducted for confined zone

a Described in Dawson and Istok, 1991
b Described in Kruseman and de Ridder, 1990
t = time since start of pumping, S' = aquitard storativity, D'= saturated thickness of aquitard, D = saturated thickness of the ground water zone, K'= hydraulic conductivity of aquitard

Table 4.10 Pumping tests, variable discharge.

METHOD*	APPLICATION	ASSUMPTIONS	REMARKS
Birsoy and Summers (1980)	-Confined -Transient -Pumped step-wise or intermittently at variable rates	-General assumptions for confined ground water zones	Tedious process
Aron and Scott (1965)	-Confined -Transient Discharge rate decreases	-General assumptions for confined ground water zones -Discharge rate deceases with time sharpest decrease occurring soon after the start of pumping	Analogous to the Jacob Method
Hantush (1964)	-Confined -Transient	-Standard assumptions for confined ground water zones -At the start of the tests, the water level in the free flowing well drops instantaneously. At t> 0 drawdown is constant and its discharge rate is variable	
Hantush-De Glee Method (Hantush, 1959b)	-Leaky -Transient -Fully penetrating well	-Standard assumptions for leaky ground water zones (see leaky section) -At the start of the tests, the water level in the free flowing well drops instantaneously. At t >0 drawdown is constant and its discharge rate is variable	

* Methods described in Kruseman and de Ridder (1990).

Table 4.11 Methods of analysis for pumping tests with special conditions.

GROUND WATER ZONE CONDITION	***FLOW***	***TYPE***	***MODELS & SOURCES***[2]
One or more recharge boundaries	Steady State	Confined or Unconfined	Dietz (1943)
One or more straight recharge boundaries	Unsteady State	Confined or Unconfined	Stallman (in Ferris et al., 1962)
One recharge boundary	Unsteady State	Confined or Unconfined	Hantush (1959a)
Bounded by two fully penetrating boundaries	Unsteady State	Leaky or Confined	Vandenberg (1976 and 1977)
Wedge shaped ground water zones	Unsteady State	Confined	Hantush (1962)
Water table slopes	Steady State	Unconfined	Culmination Point Method (Huisman, 1972)
	Unsteady State	Unconfined	Hantush (1964)
Two layered ground water zone, unrestricted cross flow Pumping well does not penetrate entire thickness	Unsteady State	Confined	Javandel-Witherspoon (1983)
Leaky two-layered ground water zone , separated by aquitard with cross-flow across aquitard	Steady State	Leaky	Bruggeman (1966)
Large diameter well	Unsteady State	Confined	Papadopulos (1967), Papadopulos and Cooper (1967)
Large diameter well	Unsteady State	Unconfined	Boulton and Streltsova, (1976)

2 Methods are described in Kruseman and de Ridder, 1990.

Table 4.12 Recovery test methods (discussed in Kruseman and de Ridder, 1990).

METHOD	***APPLICATION***	***SOURCE***
Theis Recovery Methods	X Confined X Unsteady state X Recovery after constant discharge	X Theis (1935)
	X Leaky X Unsteady state X Recovery after constant discharge	X Vandenberg (1975) X Hantush (1964)
	X Unconfined X Recovery after constant discharge X Late recovery data	X Neuman (1975)
	X Unconfined X Recovery after constant drawdown	X Rushton and Rathod
Birsoy and Summers	X Unconfined X Recovery after variable discharge	X Birsoy and Summers (1980)

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